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BUILDING ON 50 YEARS OF SYSTEMS ENGINEERING EXPERIENCE FOR A NEW ERA OF SPACE EXPLORATION

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ABSTRACT

Over the past 50 years, the National Aeronautics and Space Administration (NASA) has delivered space transportation solutions for America's complex missions, ranging from scientific payloads that expand knowledge, such as the Hubble Space Telescope, to astronauts and lunar rovers destined for voyages to the Moon. Currently, the venerable Space Shuttle, which has been in service since 1981, provides the United States' (U.S.) capability for both crew and heavy cargo to low-Earth orbit to construct the International Space Station, before the Shuttle is retired in 2010. In the next decade, NASA will replace this system with a duo of launch vehicles: the Ares I crew launch vehicle and the Ares V cargo launch vehicle. The goals for this new system include increased safety and reliability coupled with lower operations costs that promote sustainable space exploration for decades to come. The Ares I will loft the Orion crew exploration vehicle, while the heavy-lift Ares V will carry the Altair lunar lander, as well as the equipment and supplies needed to construct a lunar outpost for a new generation of human and robotic space pioneers. NASA's Marshall Space Flight Center manages the Shuttle's propulsion elements and is managing the design and development of the Ares rockets, along with a host of other engineering assignments in the field of scientific space exploration. Specifically, the Marshall Center's Engineering Directorate houses the skilled workforce and unique facilities needed to build capable systems upon the foundation laid by the Mercury, Gemini, Apollo, and Shuttle programs. This paper will provide details of the in-house systems engineering and vehicle integration work now being performed for the Ares I and planned for the Ares V. It will give an overview of the Ares I system-level testing activities, such as the ground vibration testing that will be conducted in the Marshall Center's Dynamic Test Stand to verify the integrated vehicle stack's structural integrity and to validate computer modeling and simulation, as well as the main propulsion test article analysis to be conducted in the Static Test Stand. Ultimately, fielding a robust space transportation solution that will carry international explorers and essential payloads will pave the way for a new era of scientific discovery now dawning beyond planet Earth.

Integrating the Ares I Stack and Designing the Upper Stage Element

Fielding an integrated launch vehicle system presents many challenges, considering it has been over 30 years since the U.S. has developed a human-rated vehicle — the remarkable, reusable Space Shuttle. However, with almost 50 years of experience leading the design, development, and end-to-end systems engineering and integration of complex launch

vehicles, NASA's Marshall Space Flight Center offers the in-house talent and unique facilities to deliver a new transportation system to meet the requirements for safe, reliable, and affordable space exploration.

The technical personnel who are housed primarily in the Marshall Center's Engineering Directorate, including a network of systems engineers, are assigned to the programs and projects that reside at the rocket center. Many Saturn and Shuttle veterans — as well as others who gained valuable hands-on experience in the 1990s by conducting technology demonstrator projects such as the Delta-Clipper Experimental Advanced, X-33, X-34, X-37, and Orbital Space Plane — work closely with industry partners to advance the capability for human access to space. The Ares Projects Office located at the Marshall Center is managing the design and development of America's new space transportation fleet, including the Ares I, which will loft Orion's crew for its first test flight in 2013, as well as the heavy-lift Ares V, which will round out the capability to leave Earth orbit once again, late next decade (figs. 1 and 2).

Fig. 1. NASA concept of the Ares I (right) and Ares V launch vehicles.

Initially, the Ares I will provide capacity for six crewmembers and limited cargo services to the International Space Station. For lunar missions, the Ares I will transport Orion and a crew of up to four astronauts to Earth orbit, where it will rendezvous and dock with the Ares V's Earth departure stage (EDS), which will transport the Altair (fig. 3). After mating, the EDS engine will perform the trans-lunar injection burn. Once in lunar orbit, the crew will transfer to the Altair to descend to the Moon's surface. After the crew's mission is complete on the lunar surface, the Altair's ascent stage will return the crew to the Orion waiting in orbit for return to Earth.

As stated in the U.S. Space Exploration Policy, NASA's 2006 Strategic Plan, and the 14-nation Global Exploration Strategy, these missions will be international in scope and purpose.[1,2,3] A recent joint study by NASA and the European Space Agency has begun the process of identifying partnership opportunities and mutually beneficial goals and objectives.[4]

Following is an overview of the Ares I integration and upper stage design progress, using capabilities and assets that are resident in Marshall's Engineering Directorate and within the Ares Projects Office, working with other NASA Centers and the U.S. aerospace industry. NASA's systems engineering approach is discussed throughout, including policies and procedures that reduce risk and result in quality products that meet the technical requirements for safety, reliability, and cost-effective operations within a set budget allocation against a carefully planned timeline.

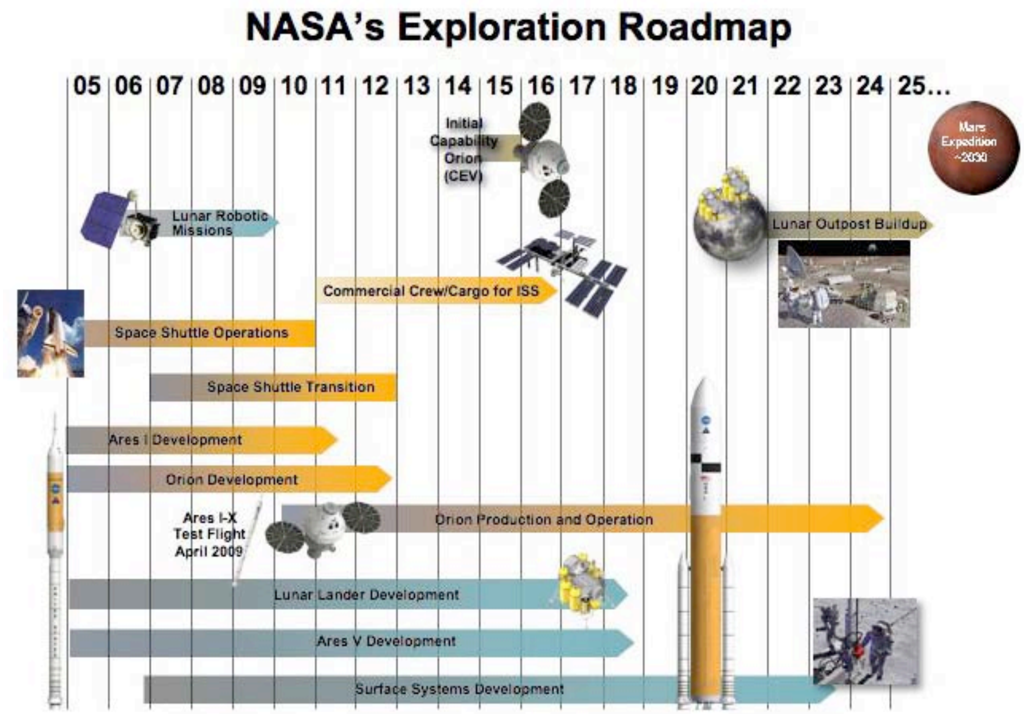

Fig. 2. NASA's exploration strategy will be realized over several decades.

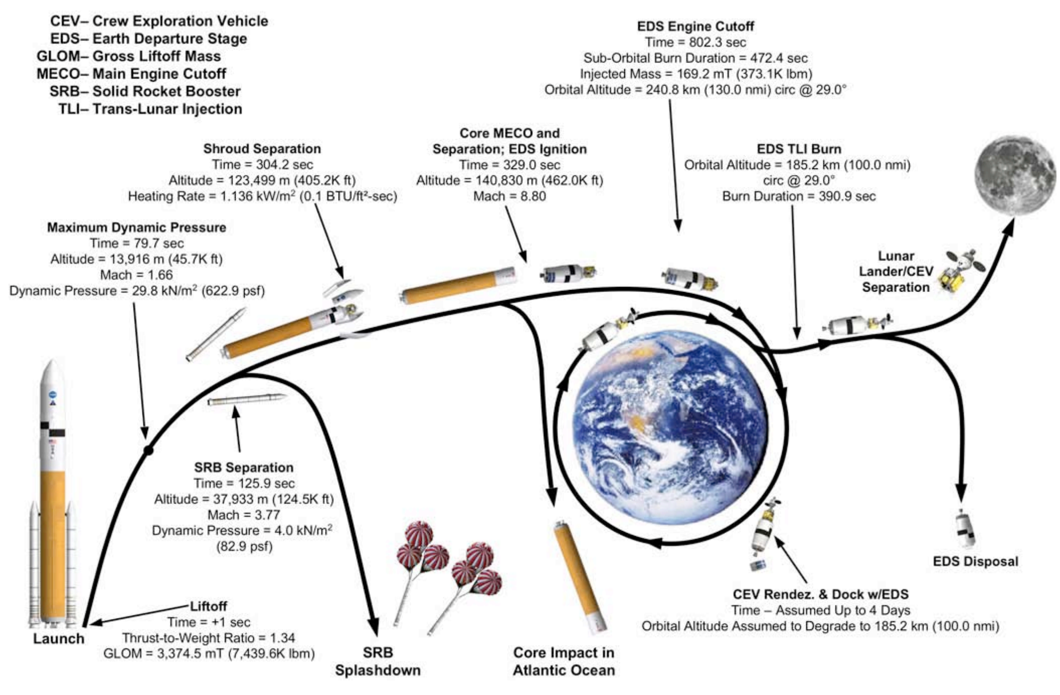

Fig. 3. Notional lunar mission scenario.

Integrating the Ares I Vehicle Stack

For reference, the Ares I is an in-line rocket configuration, with a 5-segment reusable solid rocket motor first stage and an upper stage powered by a J-2X engine, capable of putting approximately 25.5 metric tons (MT) (56,200 pounds) into orbit (fig. 4).[5] The Ares I and Ares V will have some common propulsion and structural elements; therefore, lessons derived from the Ares I design and development will yield knowledge for the heavy-lift system, which is in the advanced concept phase. It also will reduce the logistics footprint through common support equipment and associated production and handling operations.

This space transportation architecture leverages the knowledge and experience gained from tried-and-true systems, such as the Saturn V and Shuttle, while leveraging modern design tools, manufacturing processes, operational concepts, and systems engineering standards and practices (fig. 5). The Ares I first stage is an evolved 5-segment version of the existing Shuttle solid rocket motors/boosters, which are manufactured by ATK, and the J-2X engine, which is manufactured by Pratt & Whitney Rocketdyne, is based on the original J-2 utilized on the Saturn vehicles. Ares V will utilize a pair of 5.5-segment motors, and will employ the same J-2X engine as the Ares I upper stage.[6] While the Ares I upper stage is a clean-sheet design, it will be leveraged in the design of the Ares V Earth departure stage. This programmatic and technical direction will reduce recurring costs for more sustainable operations, as well as reduce the risk of developing the Ares V.

Systems engineering and integration between and among these systems is being performed in house using policies and procedures codified in NASA's Systems Engineering Processes and Requirements, Systems Engineering Handbook, and the Ares Projects Office's Systems Engineering Management Plan.[7,8,9] NASA is committed to applying systems engineering and systems management processes and standards and best practices to ensure that technical performance is accountably connected to budget allocations and schedule targets.

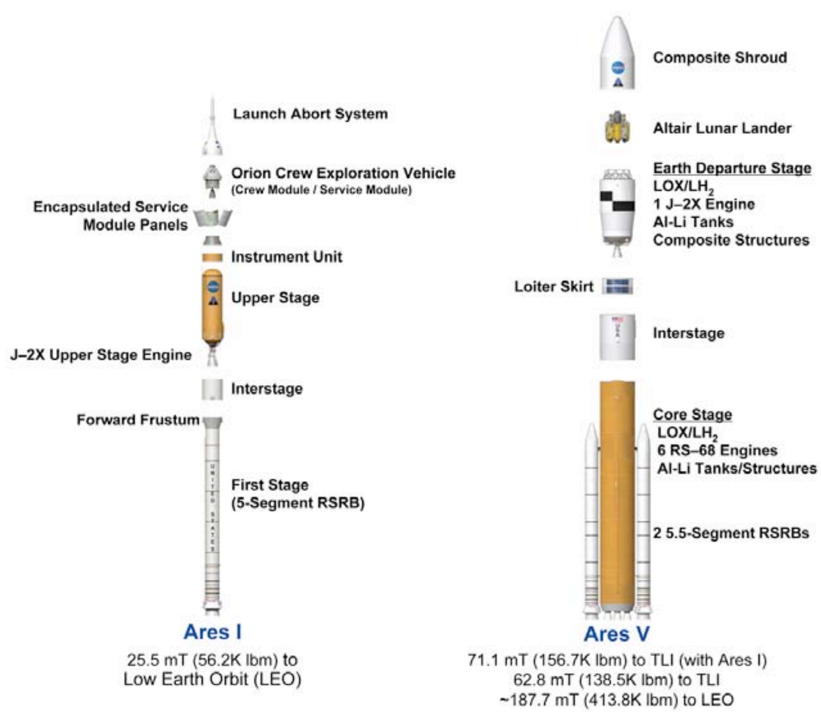

Fig.4. NASA concept of the Ares I and Ares V vehicle elements.

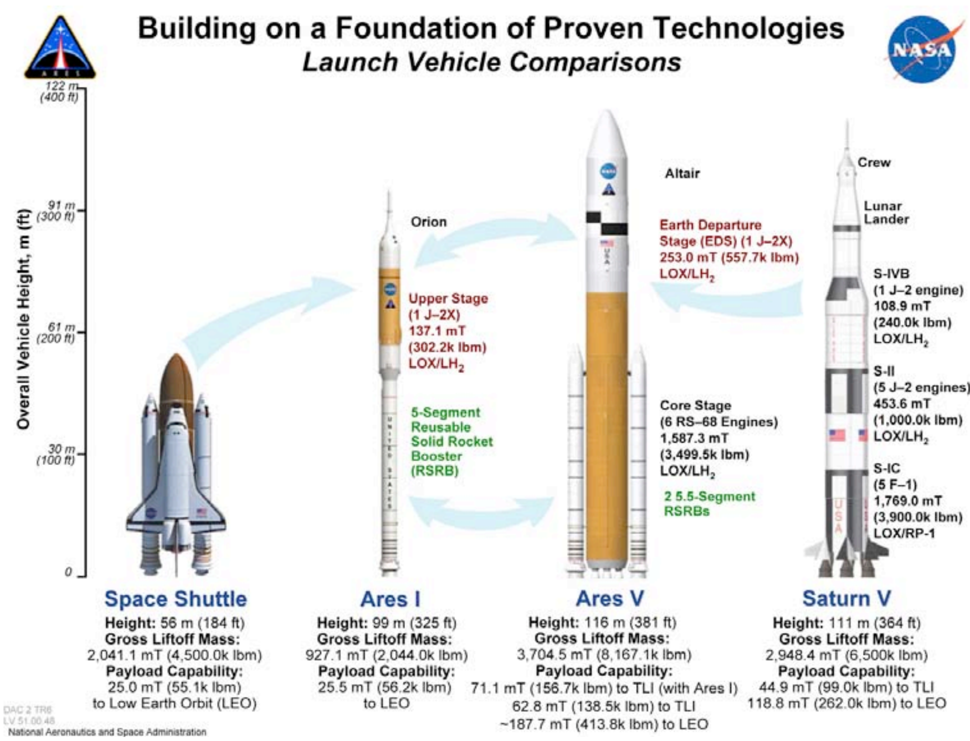

Fig. 5. The Ares I and Ares V are evolutionary space transportation solutions.

Innovation Builds on Lessons Lived

The Ares I team consists of the range of engineering and business disciplines that come together formally and informally in working groups, integrated product teams, and governing councils and boards. In this way, decision-making is handled at the lowest possible level in most cases. The various industry partners are on board and the team is fully engaged in the design and development work now in progress.

The responsibilities for Ares I systems engineering and integration is conducted by a network of primarily senior personnel who are cognizant of the "big picture" when making decisions. The Ares I vehicle systems engineering and integration function is a joint venture between the Ares Projects' Vehicle Integration Element, which incorporates the vehicle system's various hardware elements (first stage, upper stage, and upper stage engine), and the Marshall's Engineering Directorate's discipline engineers, systems engineers, and chief engineers (fig. 6). Safety and Mission Assurance representatives provide a checks-and-balances function.

Vehicle Integration responsibilities include requirements validation and verification; integrated design and analysis; configuration and data management; integrated operations and logistics; operability design and analysis; interface definition and control; and systems analysis (loads; thermal; guidance, navigation, and control; separation; and liftoff). The functions and responsibilities of systems engineering relative to project management are collaborative.

The systems engineering and integration network builds and bridges communication channels between project management and technical implementation teams, and within the various technical working groups where launch vehicle design, analysis, and testing are performed. It provides a framework for risk reduction and mission success built on the

foundation of principles and practices that position hardware and software in a disciplined enterprise, where government and contractor interests are united behind a common agenda and a shared set of expectations.

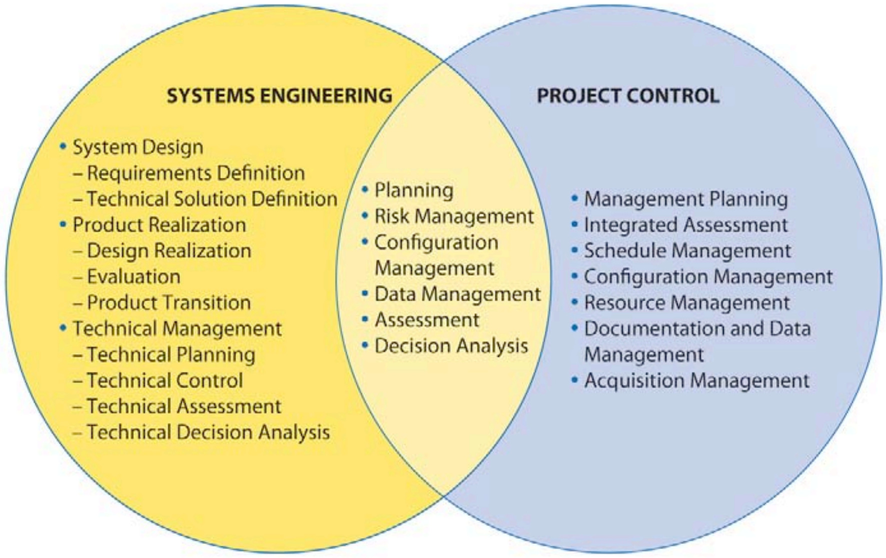

Fig.6. Systems engineering and project management roles and responsibilities are collaborative.

Much of the Ares I in-house systems engineering work is being performed by the Spacecraft and Vehicle Systems Department, which is responsible for the Ares Systems Engineering Management Plan (SEMP) referenced below. The Spacecraft and Vehicle System Engineering and Integration Division is responsible for the integrated vehicle design, design process, and subsequent functionality of the Ares I. It performs:

- Technical characterization of the complete vehicle by using lessons learned, applying engineering standards, and performing empirical and analytical analysis to verify the system.
- Vehicle technical design from concept through post-flight performance assessments.
- Integrating elements, element interconnections, ground stacking and launch facilities, and operation process design drivers.
- All major integrated vehicle development milestones (covered below).
- Vehicle systems engineering support to ground operations, launch support reviews, hardware acceptance reviews, and so forth.

To achieve these objectives, the Spacecraft and Vehicle System Engineering and Integration Division is responsible for vehicle systems design integration; vehicle system analysis and attributes; systems engineering planning and control; and vehicle hardware development and evaluation. It touches every component, part, subsystem, and system in the entire vehicle, while iterating information throughout the range of disciplines through formal design analysis cycles that are managed by a disciplined configuration control process, which is credited in *The Secret of Apollo* as a prime risk-reduction factor in the early days of space flight. (fig. 7).[10]

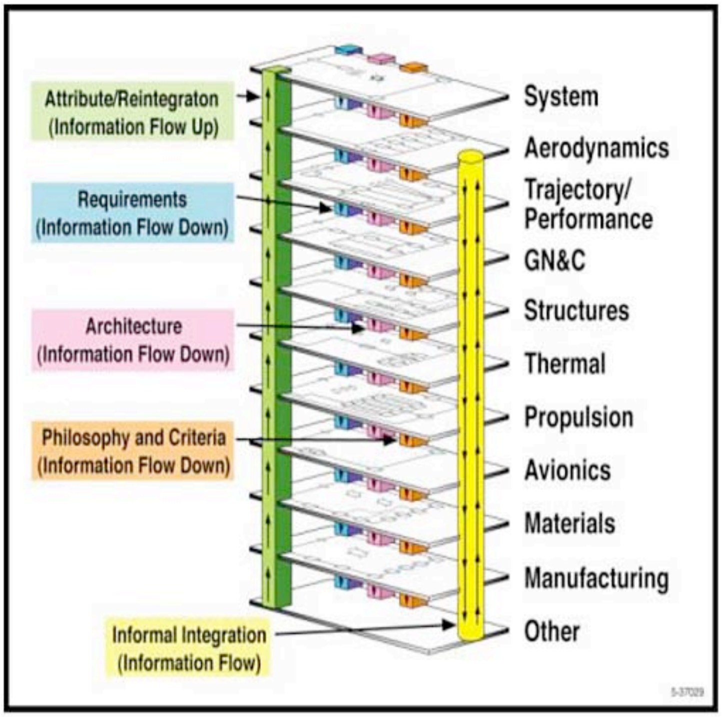

Fig. 7. Systems engineering is a non-linear, iterative process that bridges disciplines, both horizontally and vertically.

<u>Principles and Practices</u>

Three guiding documents codify NASA's principles and processes for this extensive development effort: NASA Systems Engineering Processes and Requirements, NASA Procedural Regulation (NPR) 7123.1A; NASA Systems Engineering Handbook, Special Publication (SP) 6105; and the Ares Projects Office Systems Engineering Management Plan, Constellation Program 72018. These comprehensive engineering doctrines describe both NASA's overarching philosophy and the implementation of systems engineering across its programs and projects.

Processes include interface optimization, risk management, and configuration control. With these and other responsibilities in mind, systems engineering creates an environment for mission success by balancing requirements on paper and numbers in spreadsheets, bringing concepts from virtual reality to hardware delivery. These and other applicable standards provide the rules of engagement to foster clear communications between and among team members and partners.

<u>Major Systems Engineering Milestones</u>

Although books may carefully capture processes, they are no match for the real-world experience of designing hardware and software and sharing that frame of reference with new generations of rocket scientists. Bringing together component and subsystems into the larger framework, major systems engineering milestones help mark progress and represent the culmination of thousands of hours of effort by hundreds of team members.

In November 2006, the Ares I team completed the System Requirements Review (SRR), which focused on requirements validation and verification, and risk identification and mitigation, as well as defining the reference vehicle design from which to continue systems engineering work (fig.8). In October 2007, the Ares team completed the second major milestone — the System Definition Review (SDR), which assured that the Ares I System Requirements Document was clear, achievable, responsive, and appropriate to fulfill mission needs. The Preliminary Design Review (PDR)

was conducted in mid 2008, with the Ares Board to convene in September 2008. The objective of the Ares I PDR was to provide a solid set of specifications, preliminary designs, and verification plans to take the Ares I forward into the final design phase. The PDR demonstrated that the hardware design is capable of meeting vetted requirements, as well as satisfy cost targets, operability concepts, and system availability.

Preparing for reviews involves a process for identifying and mitigating business and technical risks at the appropriate level. An example of top-level systems engineering and integration is embodied in the Engineering Information Center, where personnel who are assigned to various disciplines/work breakdown structures provide status and issues on a range of parameters. As NASA's fifth Administrator Robert Frosch, who was responsible for the development of the Space Shuttle, observed "Systems, even very large systems, are not developed by the tools of systems engineering, but only by the engineers using the tools."[11]

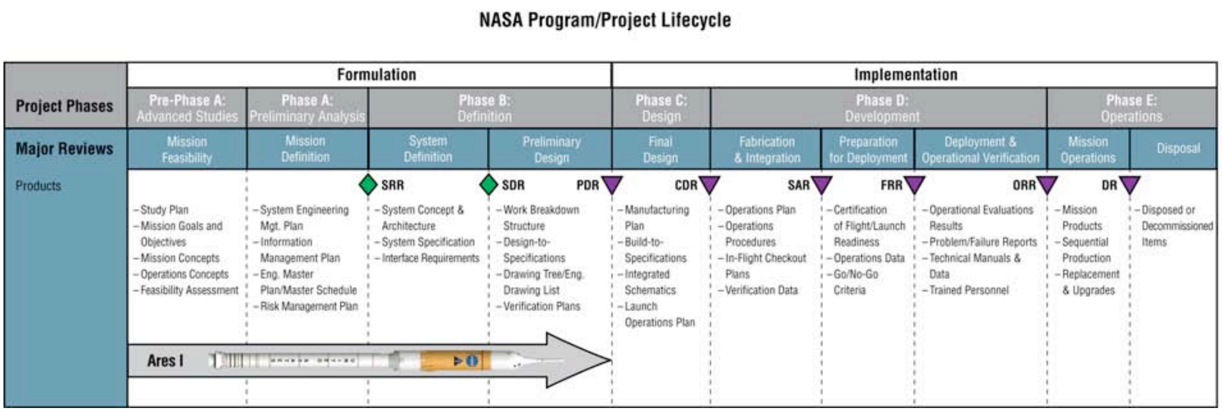

Fig. 8. Ares I systems engineering reviews, both completed and forthcoming.

Based on industry best practices, the EIC is a management tool that sets and resets the planning required to deliver excellence in engineering, based on current, first-hand knowledge, often in a raw, undigested format. In many ways, it reflects Frosch's observation that "engineering is an art, not a technique; a technique is a tool," as it is a tangible physical environment that is structured for dialogue and bottom-line understanding of the complexities of judgment in the systems engineering field. EIC participation sets the stage for the Engineering Directorate's expectations for technical excellence across the hundreds of employees who are engaged in multi-faceted expertise that goes into the vehicle system design.

It also provides a focal point for communicating a range of metrics, from resource allocations to product deliverables. This environment serves as an entrance point from the engineers conducting the design and integration work performed for the Ares Projects, as it mirrors similar management risk-reduction tools maintained by both the Ares Projects Office, which is integrating the vehicle elements, and the Upper Stage Element, which is being designed in house.

Designing the Ares I Upper Stage

The Ares I upper stage is an aluminum-lithium alloy, self-supporting cylindrical structure that is 25.5 meters (84 feet) long and 5.5 meters (18 feet) in diameter. This second stage will provide the guidance, navigation, and control, while the J-2X upper stage engine will provide the thrust and propulsive impulse, required for the second phase of the Ares I ascent flight after the first stage separates from the launch vehicle. The upper stage includes the main propulsion system, thrust vector control, avionics and software, reaction control system for roll and

attitude control, and the separation system required to perform the first stage separation. It holds the liquid oxygen/liquid hydrogen propellants and provides the system for delivering the propellants for the J-2X engine operation. Most of the avionics will be housed in an instrument unit, which provides the mechanical and electrical interfaces between the Ares I and the Orion.

The Ares I upper stage is being designed by a NASA Design Team (NDT) and fabricated by the Upper Stage Production Contractor, The Boeing Company, at NASA's Michoud Assembly Facility. NASA is reducing development risk and cost by incorporating current state-of-the-art technologies and minimizing the need for new technology development. The resulting system is designed to have minimal proprietary encumbrances. NASA has also selected The Boeing Company as the prime contractor to produce, deliver, and install avionics systems for the Ares I upper stage. Boeing will support the NDT as the Instrument Unit Avionics Contractor (IUAC), leading the development of the Ares I avionics components. The company will also develop and acquire avionics hardware for the vehicle and will assemble, inspect, and integrate the avionics system components on the upper stage. Final integration and checkout will also take place at NASA's Michoud Assembly Facility, where the Space Shuttle's external tank is now produced and where the Saturn V tanks were made.

In 2007, the Ares I Upper Stage Element successfully completed its System Requirements and System Definition Reviews, and conducted its Preliminary Design Review (PDR) to determine the adequacy, correlation, completeness, and risks associated with the allocated technical requirements for the Ares I upper stage. The PDR demonstrated that the preliminary design meets all system requirements with acceptable risk; shows that the correct design option has been selected, interfaces identified, and verification methods satisfactorily described; and establishes the basis for proceeding with detailed design.

Upper Stage Element development activities incorporate extensive component, subsystem, and overall stage-level testing to support hardware verification and stringent human-rating requirements. The team will fabricate and assemble three major test articles: a structural test article to qualify the assembled core stage structure under simulated flight load conditions; a main propulsion test article to provide a hot-firing test bed for the development and verification of the integrated propulsion system and its related subsystems (fig. 9); and a full-scale ground vibration test structure to support the overall crew transportation system and the Upper Stage/Orion configuration dynamic characterization tests, covered below.

Fig. 9. The Ares I Upper Stage main propulsion test article will be tested in Marshall's Static Test Stand.

Ares I Testing Strategy

The Ares testing strategy is very similar to that of the Apollo/Saturn development, using a test-a-little, build-a-little approach. The objective is to verify that the design and performance of components, subsystems, and system meet requirements, demonstrate the acceptability and readiness of deliverable hardware. In keeping with the guidance for system validation and verification, engineering analyses are informed by a portfolio of integrated vehicle testing. This section gives a summary of testing accomplishments and top-level details about the full-up system-level test to be conducted at the Marshall Center's Dynamic Test Stand.

Validation Test Plans

Computer aided design programs and modeling and simulation applications are vital engineering tools; however, three-dimensional testing is integral to refining the design and certifying the hardware for flight. NASA's Systems Engineering Handbook also prescribes testing objectives throughout the design and development phases, as well as during operations. Systems engineering innovations at work today are fostered by a rich set of testing data that has been generated in parallel during the vehicle design phase.

In this way, engineering analyses are informed by a portfolio of integrated vehicle testing, from scale models in wind tunnels to major full-up-system ground vibration testing in Marshall's Dynamic Test Stand, which is covered below. The testing strategy includes a series of developmental flight tests that will progress from autonomous test flights, such as the Ares I-X mission in 2009, to those carrying crewmembers in 2013, prior to fielding in 2015.

To summarize some of the testing accomplishments that are being performed in concert with design analysis cycles, Ares discipline engineers have conducted over 6,000 hours of wind tunnel testing, using models of increasing fidelity and scale, to attain the best possible aerodynamic data for use in the vehicle design. With facilities at Marshall, Langley Research Center, Ames Research Center, and Boeing, the team has captured high-fidelity aerodynamic, acoustic, and thermal data across the full operational Mach range of the Ares I. The first J-2X engine test series was completed in 2008, as an important step in the development of that engine, which will generate 294,000 pounds of thrust with a specific impulse of 448 seconds. Data obtained are being used to refine the design of the pumps and other components.

Ares I-X Developmental Flight Test

Ares will conduct the suborbital Ares I-X test flight in 2009, which will inform the Critical Design Review in 2010. This provides an early opportunity to gather data about the dynamics of the integrated launch vehicle stack, including flight controllability. In addition, as the Kennedy Space Center transitions from the Shuttle to the Ares/Orion system, the Ares I-X mission provides an excellent point from which to perfect ground operations scenarios, including modifications to Launch Complex 39B.

The Ares I-X vehicle incorporates flight and mockup hardware similar in mass and weight to the operational vehicle. This fight test will demonstrate the ascent flight control system performance with dynamically similar hardware, determine roll control methods during flight, better characterize the stage separation environment experienced during future operational flights, perfect ground operations, and gather critical data about the flight dynamics of the integrated launch vehicle stack. The vehicle's flight profile will closely approximate the flight conditions the Ares I will experience and will aid the timing of first stage burnout, first stage separation, and upper stage ignition.

Integrated Vehicle Ground Vibration Testing

Ground vibration testing measures the fundamental dynamic characteristics of launch vehicles during various phases of flight. For the Ares I, the Integrated Vehicle Ground Vibration Test series will be conducted from 2011 to 2012 using the facility that verified integrity of the Saturn V and Space Shuttle stacks (fig. 10).

Fig. 10. The Marshall Center's Dynamic Test Stand with the Shuttle Enterprise test article (1978).

This series will measure the fundamental dynamic characteristics of the Ares I during various phases of operation and flight. Test configurations will simulate the configuration at the total predicted gross lift-off weight (GLOW) and at first-stage burnout. In the stand, the integrated test article will be supported on a soft suspension system to simulate free-free boundary conditions. Facility modifications in progress include the hydrodynamic support system, suspension and access platforms to accommodate the Ares I configuration, and lifting capabilities to enable stacking, assembly, and operations.

The Ares I test article models will be correlated with IVGVT data to support the Ares I Design Certification Review in mid-2013. The DCR supports the first crewed test of the Ares I/Orion vehicle, planned for late 2013.

Conclusion: A New Day of Discovery

Seeking the answers to age-old questions is the cause for exploration. Over the years ahead, compelling missions will expand human society into new territories and propel future discoveries. Today's missions, such as NASA's Mars Phoenix lander, are opening possibilities for astronaut exploration of the red planet. Journeys to the Moon, Mars, and beyond will be powered by the space transportation systems now in design and testing by a cadre of discipline, system, and chief engineers. America's next space fleet will be maximized for missions to the International Space Station, which has been credited by the NASA Administrator as a vital capability to prepare for extended lunar exploration.[12]

Sound systems engineering best practices are employed to effectively create sustainable transportation solutions, reducing the technical and business risks that are inevitable in such a complex undertaking. NASA's approach to integrating the Ares I vehicle stack and designing the Upper Stage in house builds on the Apollo/Saturn and Space Shuttle heritage. This will pay dividends by expanding the experience base and revitalizing leading-edge infrastructure assets for testing, manufacturing, launching, and operating a new generation of space transportation for a new day of discovery beyond Earth orbit.

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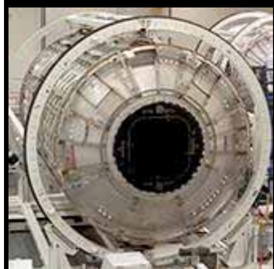
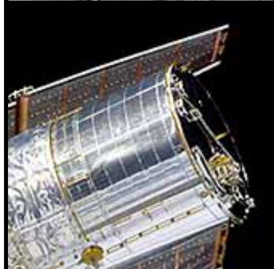
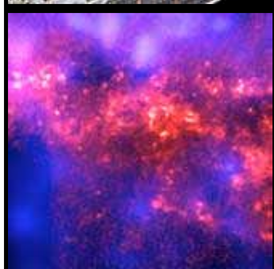





Building on 50 Years of Systems Engineering Experience for a New Era of Space Exploration

2008 International Astronautical Congress

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Agenda

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- Systems Engineering and Integration Scope
- Launch Vehicle Comparisons: 50 Years of Experience
- Designing the Ares I and the Ares V In House
- Systems Engineering Adds Value Throughout the Project Lifecycle
- NASA’s Exploration Roadmap
- Space Exploration Unites Nations

NASA Today

NASA's Strategic Goals

- **Fly the Shuttle as safely as possible until its retirement, not later than 2010.**
- **Complete the International Space Station in a manner consistent with NASA's International Partner commitments and the needs of human exploration.**
- **Develop a balanced overall program of science, exploration, and aeronautics consistent with the redirection of the human spaceflight program to focus on exploration.**
- **Bring a new Crew Exploration Vehicle into service as soon as possible after Shuttle retirement.**
- **Encourage the pursuit of appropriate partnerships with the emerging commercial space sector.**
- **Establish a lunar return program having the maximum possible utility for later missions to Mars and other destinations.**

The U.S. Space Exploration Policy

Marshall Engineering and the NASA Team

National Aeronautics and Space Administration Created by Congress in 1958

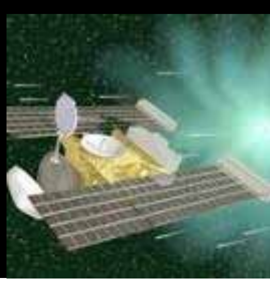
- **Led by Administrator Dr. Michael Griffin**
- **Headquartered in Washington, DC, 10 field centers**

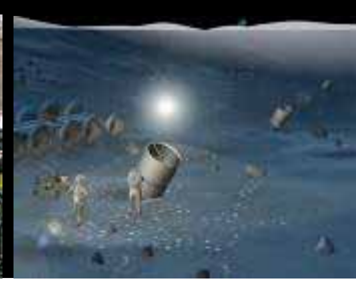
Systems Engineering and Integration Scope

As systems developer and integrator for exploration, operations, and science missions, Marshall contributes to the accomplishment of NASA's strategic goals in many ways:

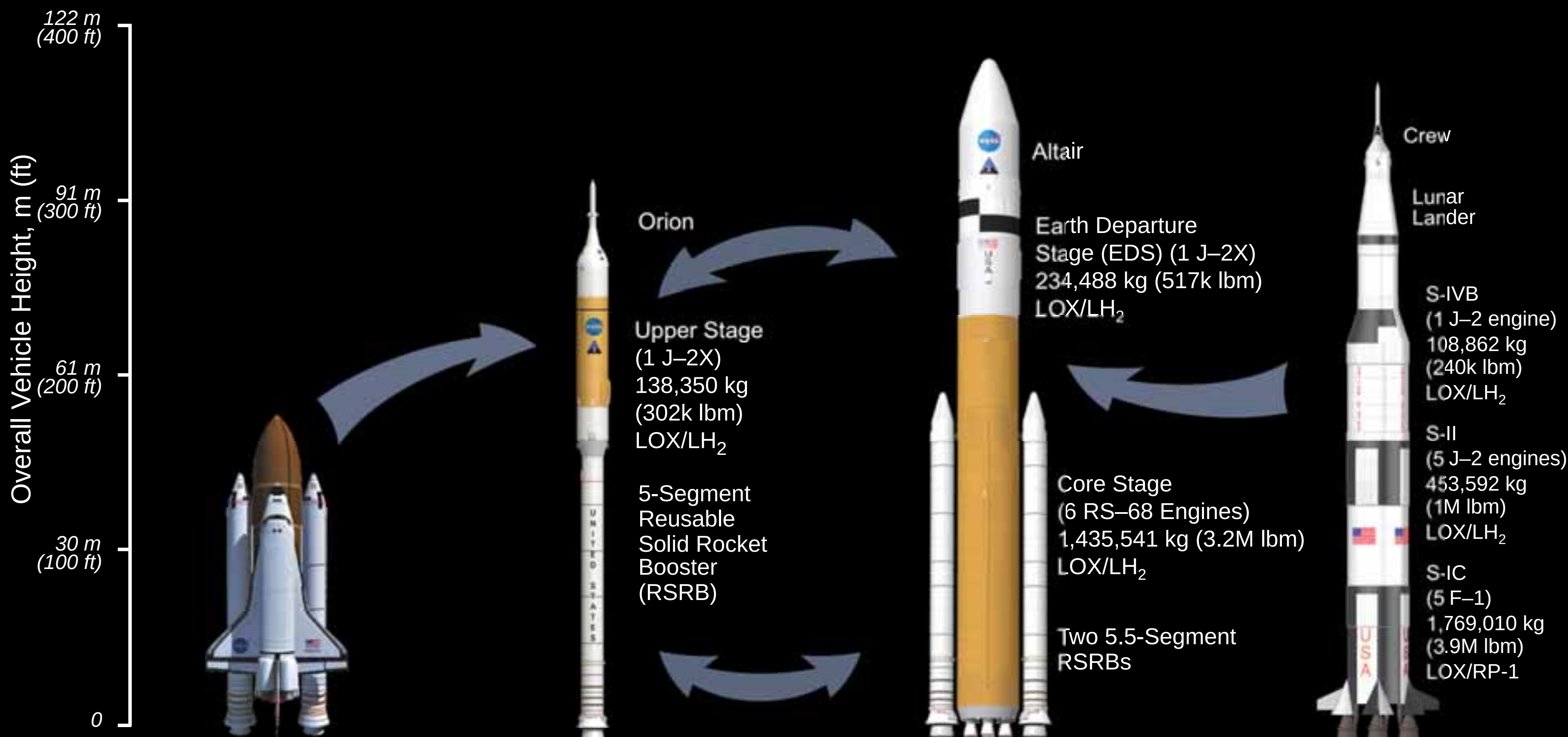


- Manages key **Shuttle** propulsion hardware and technologies
- Supports round-the-clock science operations on the **International Space Station**; element integration; and hardware and payload development
- Provides expertise in **science disciplines**, including planetary/lunar, Earth and high-energy astrophysical sciences
  - Chandra X-ray Observatory and Gravity Probe B programs
  - Discovery Program and New Frontiers Program
  - Lunar Science Program Management
- Developing **Ares I Crew Launch** and **Ares V Cargo Launch** Vehicles; support to Orion's Launch Abort Systems and Service Modules
- Supports **Lunar Exploration**
  - Manages the Lunar Precursor Robotics Program
  - Element lead for descent stage of Altair Lunar Lander
  - Subsystem lead for descent stage propulsion of Altair Lunar Lander
  - Subsystem support for ascent stage propulsion of Altair Lunar Lander
  - Support to Lunar Surface Systems

Launch Vehicle Comparisons: 50 Years of Experience



Space Shuttle
Height: 56.1 m (184.2 ft)
Gross Liftoff Mass:
2,041,166 kg (4.5M lbm)
Payload Capability:
25 mT (55k lbm)
to Low Earth Orbit (LEO)

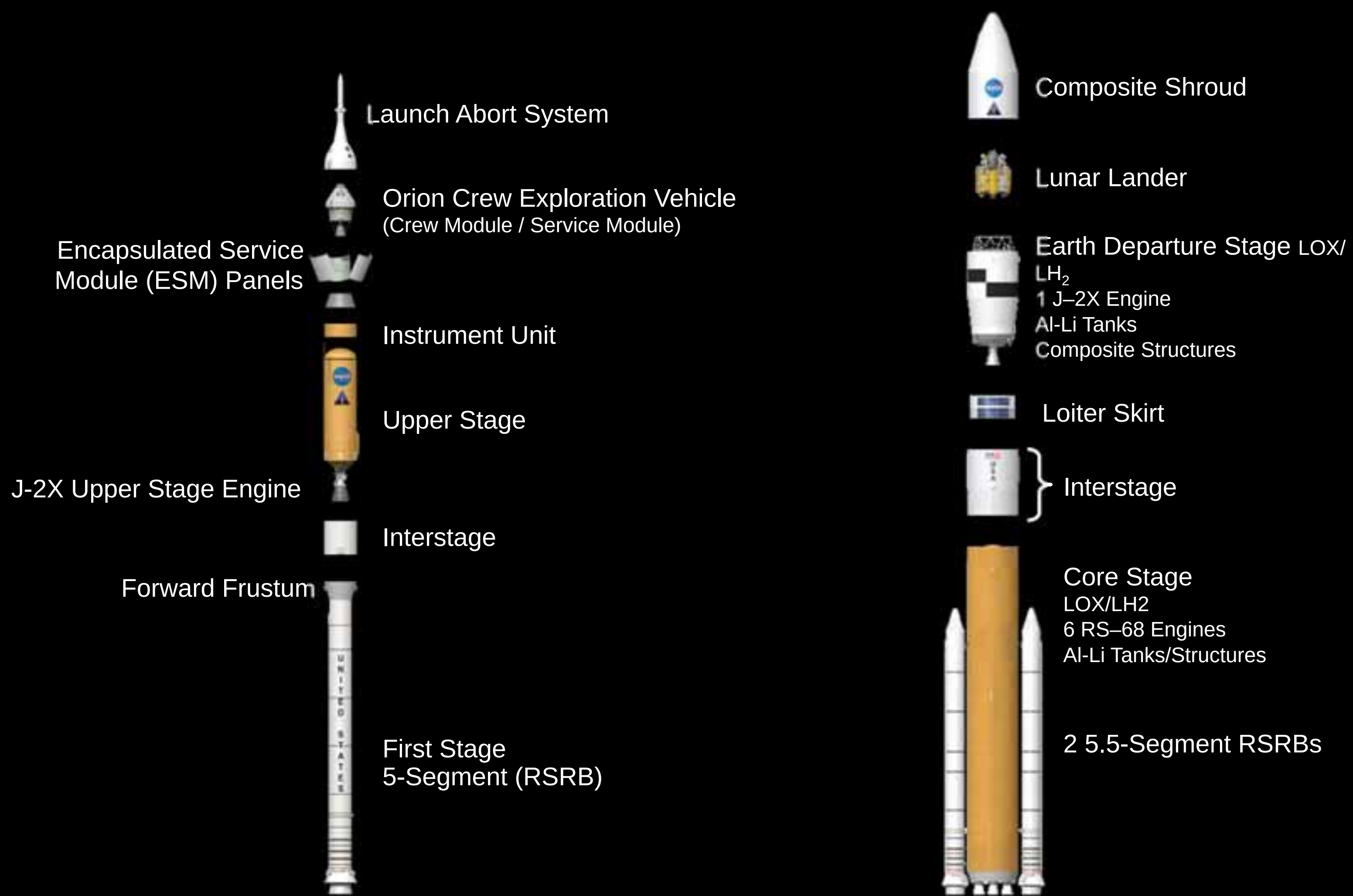
Ares I
Height: 99.1 m (325 ft)
Gross Liftoff Mass:
907,185 kg (2.0M lbm)
Payload Capability:
25.6 mT (56.5k lbm) to LEO

Ares V
Height: 116.2 m (381.1 ft)
Gross Liftoff Mass :
3,704.5 mT (8,167.1K lbm)
Payload Capability:
71.1 mT (156.7K lbm) to TLI (with Ares I)
62.8 mT (138.5K lbm) to TLI
~187.7 mT (413.8K lbm) to LEO

Saturn V
Height: 110.9 m (364 ft)
Gross Liftoff Mass:
2,948,350 kg (6.5M lbm)
Payload Capability:
45 mT (99k lbm) to TLI
119 mT (262k lbm) to LEO

The Ares I and Ares V Build on Knowledge Gained from the Saturn V and Space Shuttle

Designing the Ares I and Ares V In House

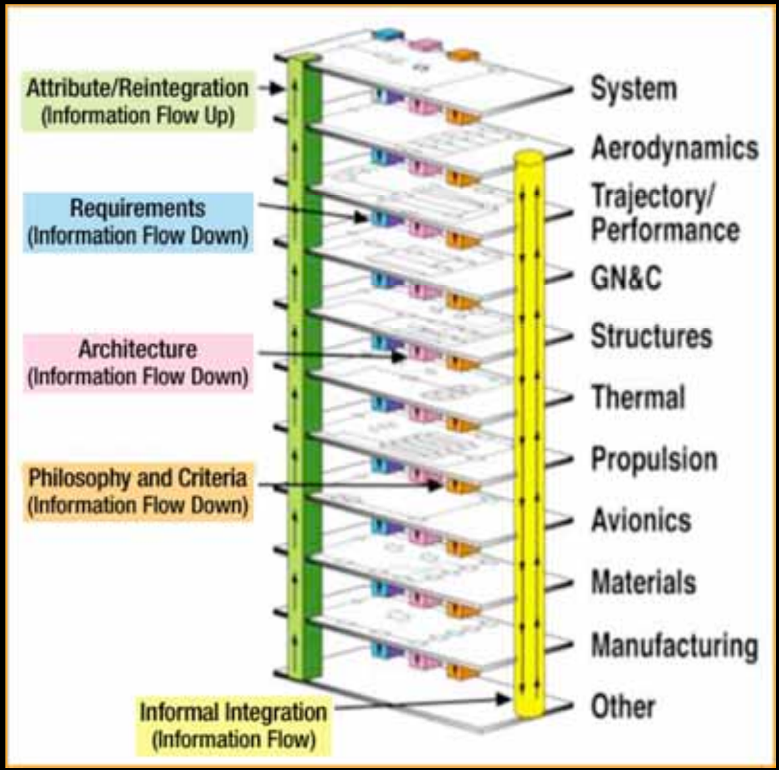


Ares I
25.6 mT (56.5k lbm) to LEO

Ares V
71.1 mT (156.7K lbm) to TLI (with Ares I)
62.8 mT (138.5K lbm) to TLI
~187.7 mT (413.8K lbm) to LEO

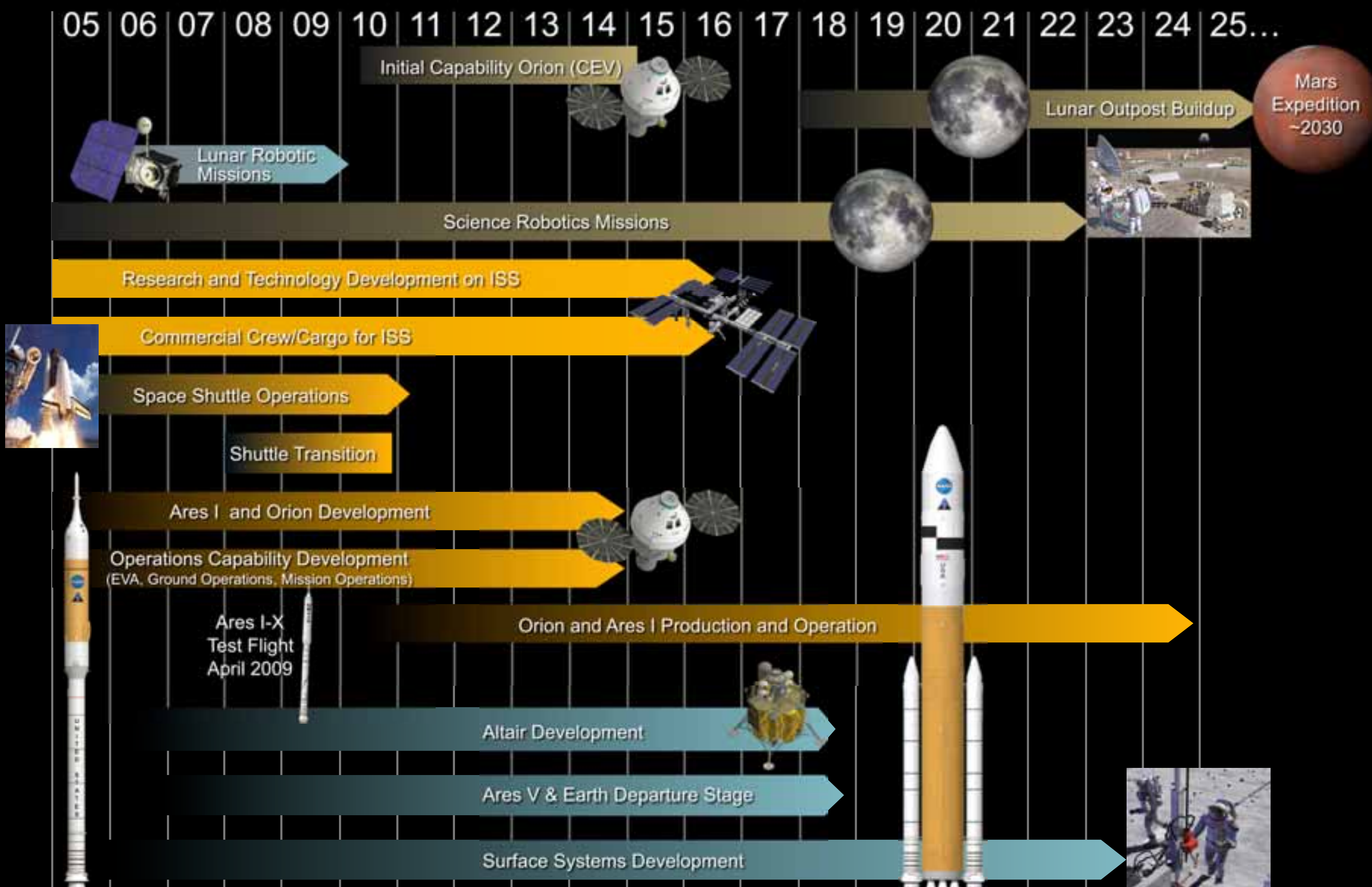
Engineering Lessons Apply to Both Systems

Systems Engineering Adds Value Throughout the Project Lifecycle



Integrating Vertically and Horizontally

NASA's Exploration Roadmap



The Exploration Timeline Spans Several Decades

Space Exploration Unites Nations

Opportunities for cooperation between countries for the peaceful pursuit of scientific knowledge and technical advancements.

The Global Exploration Strategy

For More Information

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